Dependence of persistent gaps at Landau level crossings on relative spin

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We report measurements of the quantum Hall state energy gap at avoided crossings between Landau levels originating from different conduction band valleys in AlAs quantum wells. These gaps exhibit an approximately linear dependence on magnetic field over a wide range of fields and filling factors. More remarkably, we observe an unexpected dependence of the gap size on the relative spin orientation of the crossing levels, with parallel-spin crossings exhibiting larger gaps than antiparallel-spin crossings.

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In multi-component, two-dimensional (2D) quantum Hall (QH) systems, the presence of discrete electronic degrees of freedom can significantly alter the electron-electron interaction. Recently, there has been increasing interest in the interplay between different discrete degrees of freedom in these systems. For example, the spin can influence the correlated $\nu = 1$ phase in a double layer system [1], or change the ground state symmetry of QH ferromagnetic phases at crossings of Landau levels (LLs) that originate from different confinement subbands in a wide GaAs quantum well (QW) [2]. The interplay between spin and conduction band valley has also been demonstrated, such as through the dependence of spin susceptibility on valley degeneracy in AlAs QWs [3] or the dependence of valley splitting gaps in SiGe/Si/SiGe QWs on the spins of the valley levels [4].

We studied crossings between the LLs of one valley with the lowest LL of another valley in 2D electrons in AlAs QWs. This is similar to the experiments of Ref. [2] where confinement subband crossings were studied, except we are able to vary the magnetic field position of the valley crossings, allowing us to study the field dependence of persistent gaps at those crossings. Also, the transfer of charge between different confinement subbands has a capacitive energy component due to charge redistribution along the confinement direction, whereas the valley degree of freedom has no spatial charge redistribution and, hence, no capacitive energy associated with it, yielding a somewhat simpler system. We observe an approximately linear dependence of the persistent gaps at crossings of different valley LLs on magnetic field and, surprisingly, a dependence on the relative spin of the levels, with larger gaps for the parallel spin case than for antiparallel.

Bulk AlAs has an indirect band gap with conduction band minima at the six equivalent X-points of the Brillouin zone. The Fermi surface of electrons, therefore, consists of three (six half) prolate ellipsoids (or valleys), each with its major axis oriented parallel to the crystal axis along which the valley center is displaced. Electrons occupying these anisotropic valleys have a longitudinal band effective mass of $m_l = 1.04$ and transverse masses of $m_t = 0.21$, in units of the vacuum electron mass. When confined to AlAs QWs thicker than 55 Å, as is the case for our samples, the strain associated with lattice mismatch between the AlAs QW and the GaAs substrate on which it is grown causes only the valleys oriented in the plane of the QW to be occupied up to the highest accessible densities. We will refer to these in-plane valleys as X and Y. The band effective mass, associated with the density of states and the cyclotron energy, for these valleys is given by $m_b = (m_l m_t)^{1/2} = 0.47$.

We measured two samples (A and B) from a wafer containing a 110 Å AlAs QW [5]. Each sample was patterned in a Hall bar geometry and fitted with metallic front and back gates to vary the charge density, n, from 1.5 to 8.2 x 10^{11} cm^{-2}. Typical mobilities are near 26 m^2/Vs. Ohmic contacts were made by depositing AuGeNi and alloying in a reducing environment. The samples were thinned to approximately 150 μm and glued to a piezoelectric actuator to allow for *in situ* application of a symmetry-breaking, in-plane strain that varies the energy splitting of the two occupied valleys, as described previously [6]. We employed standard low-current, low-frequency lock-in techniques, and the samples were cooled in a pumped ^{3}He refrigerator with a base temperature, T, of 0.3 K that was equipped with a single-axis tilting stage, allowing for variation of the angle, θ, between the sample normal and the applied magnetic field, B. We refer to the component of B perpendicular to the QW plane as $B_\perp$.

To locate and study the crossings of the LLs corresponding to the two occupied valleys, we employed two different methods. The first is demonstrated in Fig. 1 for sample A. We set the valley splitting to a particular, fixed value by applying a fixed voltage to the piezo [7]. The energy level (fan) diagram for the system then looks qualitatively like that shown in Fig. 1(c), with the LLs of the majority (X) valley crossing the lowest LL of the minority (Y) valley at various $B_\perp$. Some of the filling factors, ν, defined as the number of occupied LLs below the Fermi energy, E_F, are indicated in the diagram as well. Since the magnetic field corresponding to a given ν, $B_\perp^\nu = hn/e\nu$, depends on n, we can change the energy gap for an integer QH state at a particular ν by changing n. This gap is a local minimum when $B_\perp^\nu$ falls at the LL

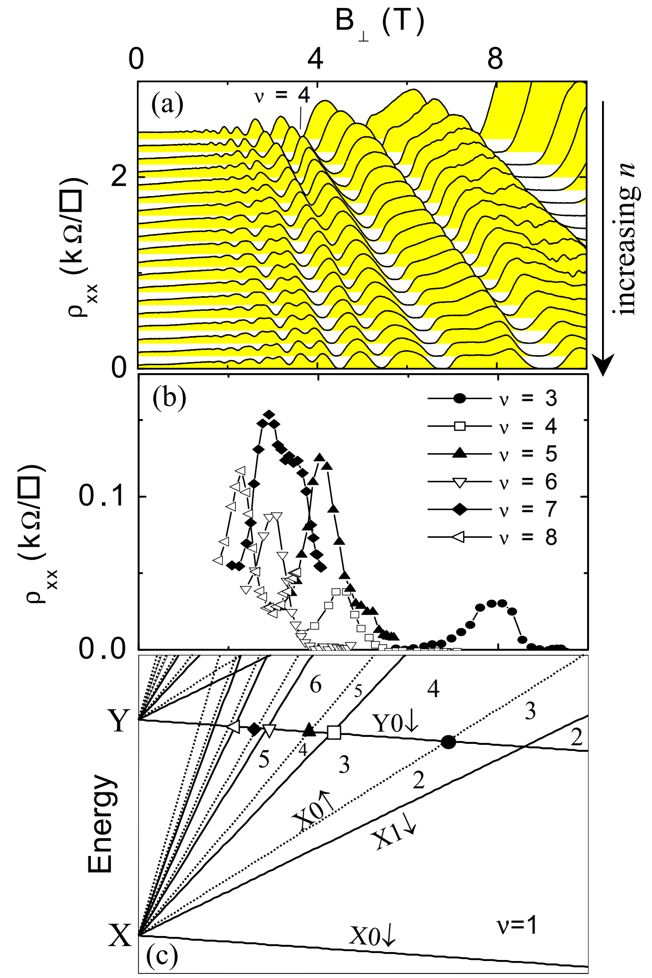

FIG. 1: (a) ρ_{xx} vs. $B_\perp$ at $T = 0.3$ K as n increases from 3.5 (top) to 6.6 x 10^{11} cm^{-2} (bottom). Traces are vertically offset for clarity. (b) ρ_{xx} at integer ν extracted from the traces in (a). (c) Simulated energy level diagram (energy units are arbitrary) for the data in (a) and (b), showing reasonable agreement between the indicated LL crossings and the extrema in ρ_{xx} at integer ν. Solid (dotted) lines are majority (minority) spin LLs, and parallel and antiparallel LL crossings are shown by open and closed symbols respectively. Our notation indicates the energy levels' valley, LL index, and spin.

crossing for that ν. Consequently, ρ_{xx} at ν should be a maximum for a particular value of n, thereby revealing the field position of the LL crossing. In Fig. 1(a), we show traces of ρ_{xx} vs. $B_\perp$ as n is increased from 3.5 (top) to 6.6 x 10^{11} cm^{-2} (bottom). Tracking ρ_{xx} at different integer ν, we obtain the curves shown in Fig. 1(b), with the peak of each curve indicating the position of the LL crossing for that ν. It can be shown that the relevant quantities that determine the positions of these crossings are the spin and valley susceptibilities of each valley and the applied piezo voltage (the overall energy scale is arbitrary). To generate the diagram in Fig. 1(c), we employ recent measurements of the valley susceptibility

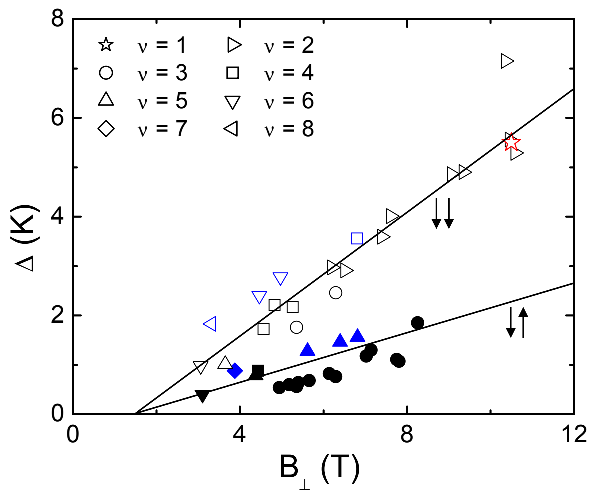

FIG. 2: Energy gaps (Δ) at LL crossings as derived from temperature-dependent activation measurements. Different symbols correspond to different ν as indicated, and open (closed) symbols are parallel (antiparallel) spin crossings. Black points are for sample A, blue for sample B, and red for a point derived from the data of Ref. [12]. The lines are guides to the eye.

in these samples [7], and use equal spin susceptibilities for the two valleys, with its value a fitting parameter [8]. The spin susceptibility is proportional to g^*m^*, where g^* and m^* are the (interaction enhanced) Landé g-factor and effective mass, and we have used $g^*m^* = 2.5$. This is enhanced by a factor of 2.7 above $g_b m_b$ ($g_b = 2$) and is in reasonable agreement with measured values in the two-valley limit [3]. The resulting fan diagram successfully reproduces the observed crossings [9].

The second method that we have employed to locate crossings between the X and Y LLs involves fixing n and $B_\perp$ so that ν is fixed at an integer value. ρ_{xx} is then monitored as the piezo voltage is swept such that the 2D electron system is taken from the strongly single-valley limit towards the two-valley limit. Along the way, the desired crossing is revealed as a local maximum in ρ_{xx}. For both methods, we have confirmed that the ρ_{xx} maxima correspond to minima of the energy gaps by measuring these gaps at and away from the LL crossings.

Our main finding is first hinted at in Fig. 1(b). The maximum value of ρ_{xx} at integer ν, attained at the LL crossings, *oscillates* with ν, with odd ν exhibiting larger ρ_{xx} peaks than even ν. From our fan diagram in Fig. 1(c), we see that the LL crossings at even ν occur between LLs with parallel spin while those at odd ν have antiparallel spin. We have further investigated this quantitatively by performing temperature dependence measurements of the persistent, activated gaps (Δ) at the LL crossings with T typically varying between 0.3 and 6 K. The crossings between LLs with the parallel spin occurring at even ν indeed appear to fall on a different, higher

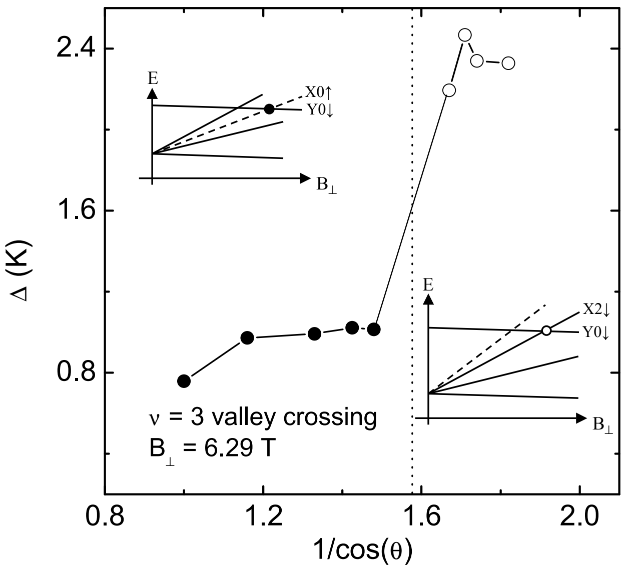

FIG. 3: Energy gap, Δ, at the $\nu = 3$ LL crossing as sample A is tilted through the first coincidence angle at fixed n and $B_\perp$. The vertical dotted line indicates the coincidence angle, and schematic fan diagrams on either side of this coincidence are shown as insets.

Δ branch than those between antiparallel spin LLs.

To further test the dependence of Δ on the relative spins of the crossing LLs, we tilted the sample with respect to B. Since the cyclotron energy, $E_C \propto B_\perp$, depends on the perpendicular component of the field while the Zeeman energy , $E_Z \propto B$, depends on the *total* field, tilting the sample causes majority (down) spin LLs to drop in energy while minority (up) spin levels rise for a given value of $B_\perp$. The result is that the different spin LLs can be brought to and driven past energetic coincidence [10], thus changing the relative spin of the LLs at the crossings. As an example, we show the gap at the $\nu = 3$ crossing as the sample is tilted in Fig. 3. Initially, the crossing at $\nu = 3$ occurs between opposite spin LLs (Y0↓ and X0↑) but, as the sample is tilted, the relative spin of the crossing LLs at $\nu = 3$ changes from antiparallel to parallel (Y0↓ and X2↓) when the first coincidence angle at $1/\cos(\theta) \simeq 1.6$ is passed. It is apparent from this data that the dependence of the size of Δ on the relative spins of the crossing LLs is preserved with tilt. The values of Δ for sample A in tilted field are included in Fig. 2.

One factor that we have neglected so far is the relative LL indices of the crossing LLs. If the finite gaps that we observe at LL crossings result from exchange-interaction induced QH ferromagnetic phases, then the symmetry of the ferromagnetic ground states and excitations, and hence the size of Δ, would depend in general on the relative LL indices of the crossing levels [11]. When these indices are different, the difference in wavefunction shape yields an easy-axis symmetry while, for same indices, the symmetry is isotropic as determined by the spin and/or valley degrees of freedom. This has been confirmed by recent observations of valley skyrmions at $\nu = 1$ in valley degenerate AlAs QWs [12]. Since the LL indices can affect the ground state symmetry and excitations of a QH ferromagnetic state, we must examine whether they are responsible for determining the sizes of the gaps. From Fig. 1(c), it is evident that all of the crossings that we have studied in sample A at $\theta = 0$ occur between LLs with different LL index except at $\nu = 3$, where both levels have LL index $N = 0$. Though there are gaps on the lower branch in Fig. 2 that correspond to crossings between LLs having different LL indices, most of the data on this branch come from $\nu = 3$. Also, when the sample is tilted, the relative LL indices for the $\nu = 3$ crossing go from being the same to being different, which could explain the change in Δ as the difference in energy between skyrmion and single-flip excitations. Similarly, the relative LL indices at the $\nu = 4$ crossing go from being different to being the same with tilt, so the reduction in Δ in that case could be explained along similar lines.

To distinguish between the effect of LL index and spin on Δ, we measured the same persistent gaps in a second sample (B). The valley splitting in sample B is larger than in sample A for a given piezo voltage due to residual strain associated with the cooldown procedure, so that LL crossings at particular ν occur at higher n and $B_\perp$ [13]. This allows us, for example, to compare Δ at ν = 2 (Y0↓ and X1↓ crossing) with ν = 5 (Y0↓ and X1↑ crossing). If we can ignore the influence of the LLs below and above E_F for the moment, then only the relative spin of the crossing levels is different for $\nu = 2$ and $\nu =$ 5. The same is true for $\nu = 1$ and 3 (Y0↓ with X0↓ or X0↑ respectively) and for $\nu = 4$ and 7 (Y0↓ with X2↓ or X2↑ respectively). We have included the measured values of Δ for sample B in Fig. 2 as blue symbols, as well as one point (red star) corresponding to the persistent gap at ν = 1 derived from the data in Ref. [12]. These additional data points confirm that it is indeed the relative *spin* of the crossing LLs that determines which of the two branches in Fig. 2 Δ falls on.

The reason for the simple yet unexpected dependence of Δ on the relative spins of the crossing LLs is not entirely clear. In a previous study of persistent gaps at crossings of different confinement subband LLs in a wide GaAs QW, a dependence on the relative spin of crossing LLs was observed and explained as a consequence of the formation of different QH ferromagnetic states [2]. That explanation relied on the difference in charge distribution along the confinement direction for the two confinement subband states, whereas such a factor does not apply for the X and Y valley subbands in our experiments. Furthermore, in our measurement the behavior of Δ away from the LL crossings is qualitatively similar for parallel and antiparallel spin crossings, both exhibiting a smooth variation reminiscent of an anticrossing.

We propose two possible explanations for the depen-

dence of Δ on relative spin that is observed in Fig. 2. The first explanation assumes that the persistent gaps are, in fact, a consequence of the formation of QH ferromagnetic states. In this case, Δ corresponds to the exchange energy cost associated with the creation of many-body excitations and, thus, depends on the strength of interaction between the electrons. The fact that Δ increases monotonically with $B_\perp$ is consistent with this interpretation, and the same idea underlies the explanation for $B_\perp$ dependent valley splitting in nominally valley degenerate 2DESs that has been reported previously [14]. The variation of Δ with relative spin, then, may be a consequence of the difference in the strength of screening of the Coulomb interaction. Lowest-order (Thomas-Fermi) screening depends only on the charges at E_F, however there exist higher-order screening processes associated with the promotion of charges from LLs below E_F to unoccupied LLs above. When the X valley LL at the crossing at E_F has minority spin, then invariably there exists a majority spin LL with the same LL index below E_F, and the electrons in this level could screen the Coulomb interaction in the corresponding minority spin LL effectively thanks to the same wavefunction shape. On the other hand, when the X valley LL at the crossing has a majority spin, there is no other LL below E_F with the same LL index, and thus the screening of the Coulomb potential by the charges in these low-lying LLs is less effective. This could produce the observed effect.

A second possibility is that some part of the finite gap results from single-particle mixing between the coincident LLs. Such mixing, associated with the existence of finite off-diagonal terms in the two-component Hamiltonian, yields an anti-crossing with a finite gap determined by the magnitude of the off-diagonal terms. Though mixing between X and Y valley states in AlAs is possible [15], it would be suppressed when the relative spins of the coincident LLs are different, since single-particle mixing between different spin states can only be facilitated by scattering from such entities as magnetic impurities or nuclear spins. Thus, in this interpretation, the difference in energy between the upper and lower branches in Fig. 2 would correspond to the mixing strength of the X and Y valley states. There are, however, several puzzling aspects in this interpretation. First, there is no obvious reason why the valley mixing should depend on $B_\perp$, as the behavior of Δ in Fig. 2 suggests it would. Second, there are still finite gaps for crossings of different spin LLs, suggesting that either there is some mixing between opposite spin states, or that there is an additional contribution to the gaps from other effects, such as the formation of QH ferromagnetic states discussed above. Finally, there is a question as to whether single-particle anticrossings are even possible in the QH regime. That would require the single-particle mixing strength of the two components at each guiding center to not vary significantly over all guiding centers and, since the mixing is almost certainly disorder-dependent, this is unlikely.

In summary, we have observed finite gaps at crossings of LLs originating from two different conduction band valleys. The size of these gaps appears to depend linearly on $B_\perp$ and also exhibits a dependence on the relative spin of the crossing levels, with parallel-spin crossings exhibiting larger gaps than antiparallel-spin crossings. The dependence on relative spin may be a consequence of variation in the strength of screening of the Coulomb interaction for these two cases, or it may signal the existence of single-particle mixing between the different valley states.

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[8] The assumption of equal susceptibilities for the two valleys means that only the positions of crossings between LLs of opposite spin are affected by our choice of our fitting parameter, the spin susceptibility.

[9] The small disagreement between the observed $\nu = 3$ crossing and the crossing in Fig. 1(c) is likely due to a slightly lower value of g^*m^* at the higher n where the $\nu = 3$ crossing occurs compared to the higher ν crossings.

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[13] At these higher values of n ($\simeq 6.5 \times 10^{11}$ cm^{-2}), the value of g^*m^* is close to 2, and LLs of different spin are close to coincidence at $\theta = 0$. We have tilted to $\theta \simeq 40^o$, which is less than the next coincidence angle that occurs at 60^o, in order to separate the different spin LLs.

[14] Δ, which is a splitting between LLs from different valleys (albeit with different LL indices and possibly different spin), appears to have a qualitatively similar (approximately linear) dependence on $B_\perp$ as previous measurements of valley splitting in nominally valley degenerate AlAs QWs [Y.P. Shkolnikov *et al.*, Phys. Rev. Lett. **89**, 226805 (2002)] and Si metal-oxide-semiconductor field-effect transistors (Si-MOSFETs) [V.S. Khrapai *et al.*, Phys. Rev. B **67**, 113305 (2003)].

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